Fermilab

Doc Number: Beams-doc-StudyAct
Version: 0.21
Category: Note

Activation of Steel and Copper Samples in the Main Injector Collimator Region

Bruce C. Brown
Accelerator Division, Main Injector Department
and
Vernon Cupps
ES&H Section, Radiation Analysis Facility
Fermi National Accelerator Laboratory *
P.O. Box 500
Batavia, Illinois 60510

27 September 2011

*Operated by Fermi Research Alliance under contract with the U. S. Department of Energy

Contents

Abstract

We study the activation of copper tags and steel tags fabricated from the Main Injector laminations by the flux of secondary particles near Main Injector collimator C307. 1.5″ diameter and smaller tags were activated for periods from 3 to 28 days. Two locations are used for the activation, providing different activating spectra and rates. Using a HPGe detector at the Fermilab Radiation Analysis Facility (RAF), we measure and analyze the γ ray spectra to identify the isotopes which have been produced. Normalization to the flux is accomplished by activation studies on Al tags. Detailed decay corrections are aided by pulse-by-pulse loss measurements with the Beam Loss Monitor device LI307. Copper and steel dominates the regions where beam loss activates the Main Injector tunnel so this will help identify the isotopes which dominate the residual radiation. This work is in parallel with a simulation study with MARS[1][2] and DeTra[3] which informs the measurements. The combination of simulation and measurement will benchmark the simulation system.

1 Introduction

In the Main Injector tunnel, we have localized beam losses which create residual radiation of sufficient levels to require analysis when planning tunnel installation and maintenance activities. In order to better understand the observed residual radiation cool down[4], [5], [6], [7], we have activated samples of copper and of Main Injector lamination steel in secondary fluxes produced by loss of 8 GeV protons. Measurements of the resulting gamma spectrum with a HPGe detector allow the identification of the isotopes produced.

A series of detailed residual radiation cool down measurements have been carried out near Main Injector Collimator C307. Beams-doc-3717 [7] reports on some of these. A high range Geiger counter for these studies was placed at a forward location ("Unshielded") downstream and above the end of the stainless steel core of C307. Another counter ("Shielded") was placed outside the marble shield on the aisle side above the beam line at approximately the longitudinal center. Images of these locations are provided in Appendix A. Differences in the cool down shapes for residual radiation at these locations were reported[7]. We chose these locations for the activation study since they experience different spectra of secondary particles as well as very different rates.

The Radiation Analysis Facility has a shielded box for operation of the HPGe spectrometer. Routine studies using 1.5″ diameter Al disks (tags) employ convenient mounting hardware which is well understood. This study was designed to use this hardware. Initial measurements revealed that multi-week exposures of steel and copper using the same diameter disks resulted in initial activities beyond the rates permitted by the system dead time. These disks were cooled down to provide information on longer half life isotopes. Smaller disks ("Nubs") were fabricated and exposed for shorter times to allow measurement of short half life isotopes.

Since the spatial pattern of beam loss at C307 remains constant, sampling the loss at Beam Loss Monitor (BLM) LI307 (integrated for each beam pulse) provides the time history of the activation. In a separate study (Beams-doc-ActAnal) we have measured the secondary hadron flux at the "Shielded" location and related it to the loss recorded by LI307 and to the beam lost on C307 using the Al activation technique. Using the tools developed in [4], we can provide a decay correction for activation of isotopes with half life greater than a couple of hours. We will correct the measured isotope spectra using this information.

Table 1: Nominal Parameters for 1.5″ Activation Analysis Disks

Aluminum Disks				
Density	2.7	gm/cm^3		
Diameter	1.5	in	38.1	mm
Mass	2.31	gm		
Volume	0.86	cm^3		
Thickness	0.08	cm	29.54	mils
Steel Disks				
Density	7.85	gm/cm^3		
Thickness	60	mils	1.52	mm
Diameter	1.5	in	38.1	mm
Volume	1.74	cm^3		
Mass	13.64	gm		
Cu Disks				
Density	8.94	gm/cm^3		
Thickness	44	mils	1.12	mm
Diameter	1.5	in	38.1	mm
Volume	1.27	cm^3		
Mass	11.39	gm		

2 Creating and Placing Samples

2.1 Cu and Al Samples

Activation analysis samples (tags) of pure Al and pure Cu have been secured and labeled by the Radiation Safety Group. Cu samples were obtained from Vernon Cupps at RAF. Al Samples were obtained from both Vernon Cupps and from Gary Lautenschlager. Each tag has a number imprinted (stamped) on its surface. Records are available for the source of each numbered tag. Table 1 gives the nominal properties of the tags. The measured mass of the samples removed on July 22 was 3.058 and 3.048 gm for Al tags and 10.797 gm for the Cu tag.

2.2 Steel Samples

To provide a definite source of steel for analysis, we selected the lamination steel used for Main Injector dipoles, quadrupoles and sextupoles. We have taken one sextupole lamination (1.52 mm nominal thickness) and cut 1.5″ diameter tags using a water jet cutter. These tags have a nominal weight of 13.64 grams. The tag removed on July 22 has a mass of 13.306 gm. Each sample was then numbered using stamps. For smaller tags, we used one of the steel tags (and one of the Cu tags) and punched smaller circular disks (somewhat deformed from flat by the punch). Sample diameters are shown below for the smaller samples.

In view of the critical magnetic performance requirements on the Main Injector steel, careful chemical analysis was performed on each heat (batch) of the steel. Table 2 provides the reported chemical analysis on one run of the steel. We believe the samples used for this activation study are typical of the whole production. This report will assume that any chemical variations are small

Table 2: Chemical Analysis of Main Injector Steel Prepared By LTV Steel on 2/22/1995. It reports values from 16 steel slabs from 8 heats in FERMI RUN 6 production for Main Injector. Weight percent is the average for the 16 slabs.

Element	weight percent	Uncertainty on weight %	Std Atomic Weight	molar percent	molar fraction
Fe	Balance		55.845		9.907E-01
C	0.0033	0.0008	12.0107	0.000709738	7.097E-06
Mn	0.5200	0.0100	54.938045	0.5115549	5.116E-03
P	0.0510	0.0030	30.973762	0.028286541	2.829E-04
S	0.0060	0.0010	32.065	0.003445071	3.445E-05
Si	0.3600	0.0100	28.0855	0.181050766	1.811E-03
Al	0.2760	0.0290	26.9815386	0.133349533	1.333E-03
N	0.0023	0.0002	14.0067	0.000576872	5.769E-06
Sb	0.0330	0.0027	121.76	0.071950577	7.195E-04

compared with other measurement uncertainties. We note that the analysis form used for each slab listed percent values for several other elements but the quantities were not transferred to the summary. We believe that the amounts show may have represented limits but in any case those elements are unlikely to be significant.

2.3 "Unshielded" and "Shielded" Sampling Locations

Packets of tags for activation analysis were prepared. For placement at the "Unshielded" (downstream above beam line) location, they sit on the vacuum weldment for the C307 collimator at about 50 milliradian angle with respect to the lost proton interactions (assuming interactions take place at the end of the tapered portion of the vacuum weldment, $14''$ from the upstream end). The "Shielded" location is on the aisle side of C307 just above the aluminum support channel for the marble, near the longitudinal center. This puts them $14''$ above beam height, $27''$ from beam center line and about $18''$ downstream of the interaction point. This suggests we are sampling deep in the shower at about 60^o from the beam direction. The shielding is provided by the iron and marble which surrounds the stainless steel vacuum box in which the lost beam interacts.

2.4 Samples placed on June 7

Table 3 lists the samples installed on June 7, 2011 to begin activation studies.

Table 3: Activation Samples Installed on June 7, 2011

Sample	C307 Shielded	C307 Unshielded
Al	#5954	#5955
Cu	#1617	#1618
Fe (first)	#001	#002
Fe (second)	#011	#012

These samples were removed at various times as shown below.

2.5 Samples placed on July 22

In response to the discovery that the initial samples were too radioactive for measuring short half life isotopes using the RAF HPGe spectrometer, a new set of samples was prepared. Lower counting rates were achieved by reducing the exposure time and by creating samples with smaller diameters. Cu samples were punched from Cu tag #1623 while Steel samples were punched from tag #018. Other tags are identified by the punched id. The range of sample sizes was selected to cover the uncertainty in when an additional access would be possible. The reduction in expected activation is indicated in the 'Fraction' column by showing the ratio of area (or weight) for this tag compared with the 1.5″ diameter tags of the same material. Each punched tag has a unique size (shown by the diameter of the punch in inches) to aid identification. Table 4 describes the samples installed on July 22.

Table 4: Activation Samples Installed on July 22, 2011

Sample	C307 Shielded	Fraction	C307 Unshielded	Fraction
Al 1.5″	#6271		#1612	
Cu 1.5″	#1621		#1622	
Steel 1.5″	#003		#004	
Cu	#1623 13/16	0.2934	7/32	0.0214
Cu	#1623 1/2	0.1111	3/16	0.0156
Steel	#018 13/16	0.2934	7/32	0.0214
Steel	#018 1/2	0.1111	3/16	0.0156

3 Removing and Measuring Samples

This study was accomplished while the HEP Program required storage of PBar beam in the Recycler Ring. Access to the Main Injector tunnel was restricted since entry required that the 'stash' of antiprotons be used or destroyed. Coordination with the program requirements was achieved with the help of the Run Coordinators.

3.1 Samples Removed on July 5

After 28 days of exposure, we chose to remove one of the steel tags from each sample location. Fe #011 and Fe #012 were removed and delivered to the RAF for analysis. Deadtime considerations limit samples to an observed residual activity of 1 milliRad/hr. Both samples were too hot to measure on July 5. Fe #011 was measured later that week but Fe #012 remains too hot for analysis after 2 months.

Upon delivery to RAF, these tags were assigned to Work Request #: 11-162. Results from MI collimator Tag #011 are available in the report for this work request dated 8/22/2011.

3.2 Samples Removed on July 22

When the activity from the tags removed on July 5 was known, effort began to obtain the tags shown in Table 4. When access was available on July 22, 2011, we removed the remaining sample which had been installed on June 7. These samples were delivered to RAF for analysis and were assigned as Work Request #: 11-179. The results for tags Al#5954, St-#001, Cu#1617 (from

"Shielded" location) and Al#5955 (from "Unshielded" location) are in the report for this work request dated 8/31/2011. As expected, the Steel and Cu samples from the "Unshielded" location remain quite hot.

3.3 Samples Removed on July 26

An access was made on July 26 and the samples from the July 22 installation at the "Unshielded" locations were retrieved and delivered to RAF where they were assigned Work Request #: 11-181 (Al) and Work Request #: 11-182 (Cu and Steel). Reports for these two work requests are dated September 16, 2011.

3.4 Samples Removed on August 5

An access was made on August 5 and the samples from the July 22 installation at the "Shielded" locations were retrieved and delivered to RAF where they were assigned Work Request #: 11-196. Results for Al Tag #6271, Steel 13/16 and Cu 13/16 are provided in a report dated 17 September 2011.

4 Activation with Correction for Decay

The observed isotopes and their approximate abundances will be used to inform our efforts to study the decay of residual radiation on the Main Injector tunnel. For that purpose, the results provided in the RAF standard reports are sufficient. We have additional goals, however. In a parallel efforts, a study of losses in this collimator and of the production of isotopes in these samples is underway using the codes MARS and DeTra. For that purpose, the decay corrections during exposure is needed in addition to the correction applied to the reports which correct "back to the time of sampling." The technique to express the results in terms of the hadron fluence (integral of the flux) will be documented here. We will then re-express these results for activation with the simulated uniform flux for 30 days (activation decay correction) and cool down for 2 hours which is the specification we will apply in the simulations. The reader should note that without considering a cool down time, one might expect an unmanageable list of isotopes with short half life. The planning goal for major repair or upgrade activities would involve cool down from a day to a week or more as minimum. However, the monitoring techniques which have been used to develop data on the residual radiation in the Main Injector[4] involve accesses which include some measurements after about 2 hours of cool down.

4.1 Isotope Production

In a beam of particles, nuclear interactions produce new isotopes. The number of new nuclei is proportional to the fluence, Φ, measured in particles per unit area (particles-cm^{-2}). In a material with n_T target atoms per unit volume, an interaction with cross section σ_I will produce n_I atoms per unit volume of isotope I

$$n_I = \Phi n_T \sigma_I. \tag{1}$$

The activity, S_A (Bq per cm^3), produced by n_I atoms per cm^3

$$S_A = \frac{n_I}{\tau_I} = \frac{n_I \ln 2}{t_{1/2}} = \frac{\Phi n_T \sigma_I \ln 2}{t_{1/2}} \tag{2}$$

We will want the specific activity per gram of target material, $S_A = S/\rho_T$ (Bq per gram).

$$S_A(Bq/gm) = \frac{n_I \ln 2}{\rho_T t_{1/2}} = \frac{\Phi n_T \sigma_I \ln 2}{\rho_T t_{1/2}} \tag{3}$$

Substituting for n_T with $\rho_T N_A/A_T$ we have

$$S_A(Bq/gm) = \frac{\Phi N_A \sigma_I \ln 2}{A_T t_{1/2}} \tag{4}$$

$$S_A(pCi/gm) = \frac{\Phi N_A \sigma_I \ln 2}{A_T t_{1/2} 3.7 \times 10^{-2}} \tag{5}$$

4.2 Isotope Production with Decay

Equation 5 describes the activity for each isotope produced by the fluence Φ before considering the decay losses during irradiation and during cooldown. For simulations, we will assume uniform irradiation and fix cooldown times. A standard formula will apply:

$$S_A(t_c)(Bq/gm) = \frac{N_A}{A_T}\sigma_I \frac{d\Phi}{dt}(1 - e^{-t_i/\tau_I})e^{-t_c/\tau_I} \tag{6}$$

where t_i is the radiation time, t_c is the cooldown time, Φ is the fluence (integrated flux). The correction for cooldown after irradiation is expressed by the term e^{-t_c/τ_I}. Note that for $t_i \gg \tau_I$, $(1 - e^{-t_i/\tau_I}) \Rightarrow 1$, and we reach a saturation activity determined by the flux (rate or fluence per second). On the other hand, for $t_i \ll \tau_I$, we have

$$S_A(t_c)(Bq/gm) = \frac{N_A}{A_T}\sigma_I \frac{\Phi}{t_i}(1 - e^{-t_i/\tau_I})e^{-t_c/\tau_I} \tag{7}$$

which approaches

$$S_A(t_c)(Bq/gm) \sim \frac{N_A}{A_T}\sigma_I \frac{\Phi}{\tau_I}(1 - \frac{t_i}{2\tau_I})e^{-t_c/\tau_I} \tag{8}$$

showing that the activity is proportional to the fluence (rate for producing the new isotope) divided by τ_I to give the decay rate but with a correction for the decay during irradiation. We will derive formulas for non-uniform irradiation but express them so that the correction from ideal is apparent for both extremes of half life.

4.3 Activation Decay Correction Using Detailed History

We have details of the activation time history using the BLM record. We use the fluence from the activation of Al tags. To correct the measured activities for decay during irradiation, we apply the half life weighted BLM histories as follows. We sum loss per pulse (per Main Injector Cycle) using

$$LI_j = \sum_{t=t_j}^{t_j+T_s} LI(t) \tag{9}$$

where the sum interval T_s used is 10 minutes for each quanta LI_j. To account for decays, we will weight these to provide an exponentially weighted sum but express the life time using the half life

$$LW(I, T_M) = \sum_j LI_j \frac{\ln 2}{t_{1/2}} 2^{-(T_M - T_j)/t_{1/2}} \tag{10}$$

where T_M is the radiation measurement time, T_j is the quanta time and $t_{1/2}$ is the half life for isotope I. With times in seconds, LW is in units of Rads/sec. The sum loss without weighting

$$L(I,T_M) = \sum_j LI_j \frac{\ln 2}{t_{1/2}} \tag{11}$$

now allows the correction we need. We can provide the fluence or activity(corrected for decays) by

$$\frac{\Phi}{\Phi_{uncorr}} = \frac{S_A}{S_{A(uncorr)}} = \frac{L(I,T_M)}{LW(I,T_M)} \tag{12}$$

For our case of nearly uniform irradiation, this will produce a similar result as will Equation 13. For long half life isotopes, this correction will not be large and comparison of corrected and uncorrected results will be apparent.

Compare this correction for decay during irradiation with the uniform irradiation formula when expressed similarly

$$\frac{S_A(t_i)}{S_A(uncorr)} = \frac{\tau_I}{t_i}(1 - e^{-t_i/\tau_I}) \tag{13}$$

However, for short half life isotopes, with $t_i \sim \tau_I$ or even larger, this correction will become very large and the more natural comparison will be to correct the rate. We note that for long exposures, the observed activation is proportional to the rate.

4.4 Activity per Loss Unit Formula

In order to conveniently handle all the isotopes in the same fashion, we will find the weighted loss for each half life. We will (have) corrected activity for cool down decay and then report activity divided by weighted loss. Identifying the activity after correction for cool down as $S_A(meas) = S_A(uncorr)$, we will report $S_A(meas)/LW(I,T_M)$.

4.4.1 Expression for Intermediate Times

Since we will use a spreadsheet for some of the calculations for half life weighted loss, we will want to be able to select the beginning time for the exposure of interest from a table of losses beginning at an earlier time. Let us call T_s the time for starting the exposure of interest.

$$LW(I,T_M) = \sum_j LI_j \frac{\ln 2}{t_{1/2}} 2^{-(T_M - T_j)/t_{1/2}} = \sum_j^{j_s} LI_j \frac{\ln 2}{t_{1/2}} 2^{-(T_s - T_j)/t_{1/2}} 2^{-(T_M - T_s)/t_{1/2}} + \sum_{j=j_s}^{j_M} LI_j \frac{\ln 2}{t_{1/2}} 2^{-(T_M - T_j)/t_{1/2}} \tag{14}$$

$$LW(I,T_M) = LW(I,T_s) 2^{-(T_M - T_s)/t_{1/2}} + \sum_{j=j_s}^{j_M} LI_j \frac{\ln 2}{t_{1/2}} 2^{-(T_M - T_j)/t_{1/2}} \tag{15}$$

$$LW(I,T_M - T_s) = LW(I,T_M) - LW(I,T_s) 2^{-(T_M - T_s)/t_{1/2}} \tag{16}$$

5 Results

/pgph To present results which allow one to compare various exposures but are based as much as possible on a limited set of corrections, we will report results using $S_A(meas)/LW(I,T_M)$.

Table 5: Steel Sample Results

Sample	Half Life days	St #011 Shielded	St #001 Shielded	St 13/16 Shielded	St 7/32 Unsh
		S_A/LW (pCi/gm)/(Rad/sec)			
Ar-42/K-42	12020.4				1392982123
Br-76	0.675			20446.77714	
Co-60	1925.8	125187.5187	105940.1334		
Cr-48	0.898333333				222153.1138
Cr-51	27.7	245010.1823	271837.8763	242451.3012	24039254.19
Fe-52	0.344791667			1322.988563	269300.8471
Fe-59	44.5	268904.3206	294192.7459	290835.3828	
K-43	0.9292				319548.6949
Mn-52	5.591	77112.24603	98914.88615	64942.63109	7048553.439
Mn-54	312.2	543565.8771	533645.6271	531673.6862	52966453.76
Mn-56	0.1074			7419593.43	36583306.78
Na-24	0.62329			4273.697197	247468.0199
Sb-122	2.7	550171.0866	627952.3381	493593.8886	955758.1545
Sb-124	60.2	241274.3449	233152.0454	54501.8855	
Sc-44m	2.44	7720.14845	5525.314692	3037.456571	1277618.711
Sc-46	83.83	13254.16048	15748.69149		3033686.894
Sc-47	3.341	8420.425724	14087.07368	9221.844052	1215488.398
Sc-48	1.82	1657.115699		2414.911169	206489.6475
Ti-44/Sc-44	17275.85	3839025.219		21443922.69	10182005060
V-48	15.98	46454.806	48793.6764	36671.19463	5976232.916
Sc-44	0.165416667	7.068E+03		15243.2645	3225776.152
K-42	0.515				407469.3997

Table 6: Ratios for Steel Samples

		S_A/LW	Shielded			Unshielded
Sample	Half Life days	Average Shielded	St #011 /average	St #001 /average	St 13/16 /average	St 7/32 /average
Ar-42/K-42	12020.4					
Br-76	0.675	20446.7				
Co-60	1925.8	115563.8	1.083275996	0.9167		
Cr-48	0.8983					
Cr-51	27.7	253099.7	0.968037886	1.0740	0.9579	94.979
Fe-52	0.34479	1322.99				203.55
Fe-59	44.5	284644.15	0.944703486	1.0335	1.0218	
K-43	0.9292					
Mn-52	5.591	80323.25	0.960023926	1.2314	0.8085	87.75
Mn-54	312.2	536295.06	1.013557488	0.9951	0.9914	98.76
Mn-56	0.1074	7419593.43				4.9306
Na-24	0.623	4273.69				57.90
Sb-122	2.7	557239.10	0.987316005	1.1269	0.8858	1.715
Sb-124	60.2	176309.43	1.368471053	1.3224	0.3091	
Sc-44m	2.44	5427.64	1.422376684	1.0180	0.5596	235.391
Sc-46	83.83	14501.43	0.913990148	1.0860		209.199
Sc-47	3.341	10576.45	0.796148751	1.3319	0.8719	114.924
Sc-48	1.82	2036.01	0.813902144		1.1861	101.419
Ti-44/Sc-44	17275.85	12641473.96	0.303684937		1.6963	805.444
V-48	15.98	43973.23	1.05643389	1.1096	0.8339	135.906
Sc-44	0.1654	11155.585	0.633575524		1.3664	289.162
K-42	0.515					

6 Discussion

A few of the measurement results are particularly interesting. We had recognized the possibility of producing various isotopes which have half live values between 15 and 80 days. We believed that the limited residual radiation data we are able to obtain would not be appropriate for identifying these isotopes by separating the contribution to cool down measurements. We have added the half life values for ^{51}Cr and ^{59}Fe to the array of possibilities we consider for fitting residual radiation to BLM history[4]. Several other items deserve separate consideration.

6.1 Secular Equilibrium: Do we see long lived isotopes from their daughters?

We have examples of isotope pairs which can occur with production of a long lived isotope in combination with a short lived daugher. Once the originally produced daughters decay, one achieves secular equilibrium between the long lived and short lived components. We identify the decay of the short lived isotope and then must have additional data to learn about what is produced. Table 7 shows the examples in these measurements. We identify these pairs from the decays of K-42 and Sc-44.

Table 7: Secular Equilibrium Candidates

Ar-42/K-42				
Ar-42	12020.4	days	32.9	years
K-42	0.515	days	12.360	hours
Ti-44/Sc-44				
Ti-44	17275.85	days	47.3	years
Sc-44	0.1654	days	3.97	hours

In the copper samples, we only see Sc-44 in the 'Unshielded' sample (Cu-7/32) which was counted quickly. If we assume we produced Sc-44 directly, it appears at about the same rate as Sc-44m. In the steel samples, we see both K-42 and Sc-44 in the 'Unshielded' sample (Steel-7/32) which was counted quickly. We also see Sc-44 in the 'Shielded' sample (Steel-13/16) which was counted quickly and also in Steel#011. Since we have other samples which should have adequate sensitivity but were measured after more delay, most or all of the activity must be due to the production of the short lived isotopes.

6.2 Antimony Activation

Our first surprise when examining the activation of steel sample #011 was the appearance residual radiation from ^{122}Sb and ^{124}Sb. As noted in Table 2, Sb is only 0.0330% by weight. By taking the activation measurements and half life values in the measurements for Sample #011 or #001, we can see an interesting range for the effect of Sb on the observed residual radiation near activated Main Injector steel. after two days, the contribution is 25 - 50% depending on the activation history. After 60 to 90 days cool down, these results imply that the Sb isotopes contribute about 25% of the residual radiation. After some consideration, we suspect that neutron capture is responsible for much of this activation. We note that the molar fraction of ^{121}Sb is 0.5721 and for ^{123}Sb the molar fraction is 0.4279. Fortunately the high loss points in the Main Injector frequently do not have Main Injector laminations at the loss locations. Attention to this issue is needed when examining the MARS/DeTra simulation for sample activation.

6.3 How is ^{59}Fe Produced

We notice that the measured spectra include significant production of ^{59}Fe in the steel samples. Looking at the materials in the steel, we notice that pure iron includes 4 isotopes. ^{58}Fe is only 0.00282 mole fraction. We might not be surprised if the routine MARS calculation fails to sample the reaction for neutron capture on ^{58}Fe which will produce ^{59}Fe due to limited statistics. We expect to examine this carefully.

7 Summary and Conclusions

8 Acknowledgments

The contributions from Gary Lauten and the Accelerator Radiation Safety Group are gratefully acknowledged. Access for placement and removal of samples required careful coordination since access demanded that no antiprotons be in the Recycler Ring. We thank the Run Coordinators Cons Gattuso and Mary Convery for their assistance in this coordination.

A Locations for Activation Tag Placement

Figure 1: Placement of Geiger Tube for measurement of residual radiation at “Shielded” location on Collimator C307

The locations for this activation study were chosen to match spots where we have carried out a series of residual radiation cool down measurments. One of these was reported in [7]. Photos for that document allow one to identify these locations. Figure 1 shows the location for the “Shielded” activation tags. Figure 2 shows the location for the “Unshielded” activation tags.

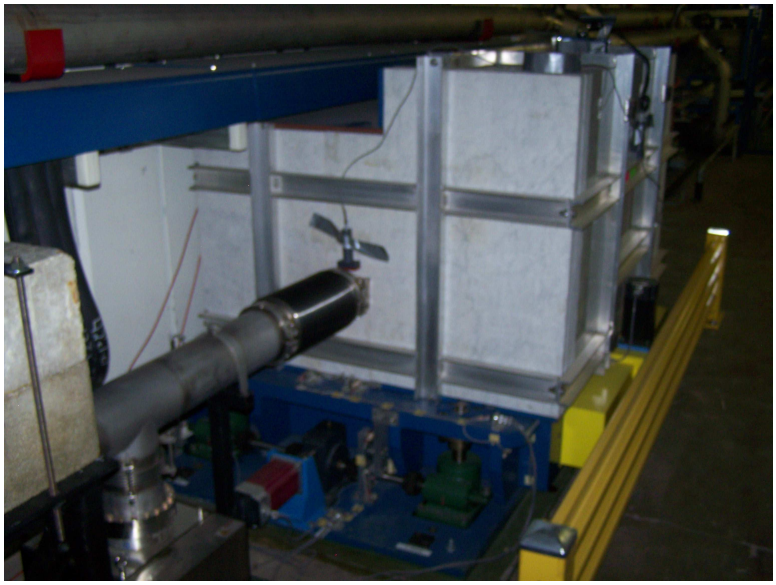

Figure 2: Placement of Geiger Tube for measurement of residual radiation at “Unshielded” location on Collimator C307

References

[1] Nikolai V. Mokhov. The MARS code system user’s guide version 13(95). FN 628, Fermilab, April 1995.

[2] N. V. Mokhov and S. I. Striganov. MARS15 overview. *AIP Conf. Proc.*, 896:50–60, 2007. Also available as FERMILAB-CONF-07-008-AD.

[3] Pertti A. Aarnio. Decay and Transmutation of Nuclides. CMS-NOTE 1998-086, CERN, January 1999.

[4] Bruce C. Brown and Guan Hong Wu. Measuring Correlations Between Beam Loss and Residual Radiation in the Fermilab Main Injector. In Jan Chrin, editor, *Proceedings of the 46th ICFA Advanced Beam Dynamics Workshop on High-Intensity and High-Brightness Hadron Beams (HB2010)*, Morschach, Switzerland, 2010. Also available as FERMILAB-CONF-10-368-AD.

[5] Bruce C. Brown. Analysis of Some Crude Main Injector Radiation Cool-down Data. Beams-doc 3219 v1, Fermilab, October 2008.

[6] Bruce C. Brown. Predicting Residual Radiation using Beam Loss Data - Early Results. Beams-doc 3568 v1, Fermilab, March 2010.

[7] Amir Jaehoon Safavi. Comparison of Short Term Cooldown Data for MI Collimator C307 Near Beam and Beside Marble Shielding. Beams-doc 3717 v1, Fermilab, November 2010.